Precision Measurement of the Low Energy Solar Neutrino Spectrum with the LENS Experiment

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for the LENS Collaboration

2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2009)
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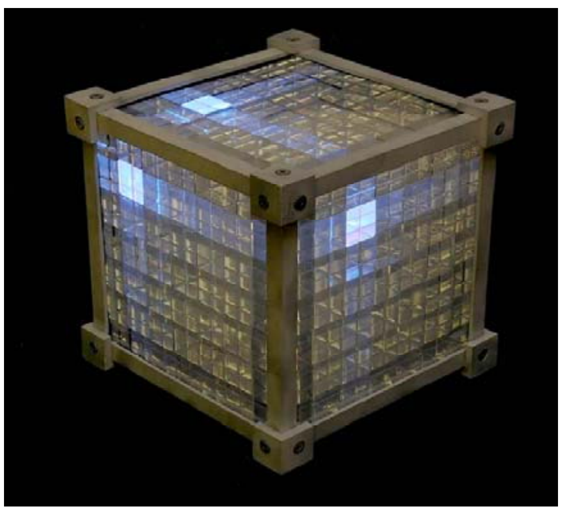


The Low-Energy Neutrino Spectroscopy (LENS) collaboration aims to **precisely** measure the **full spectrum** of low energy neutrinos emitted from the sun via real-time, charged-current interactions.

LENS is a next-generation neutrino experiment targeted towards the Deep Underground Science & Engineering Lab (DUSEL)

* Work partially supported by the National Science Foundation

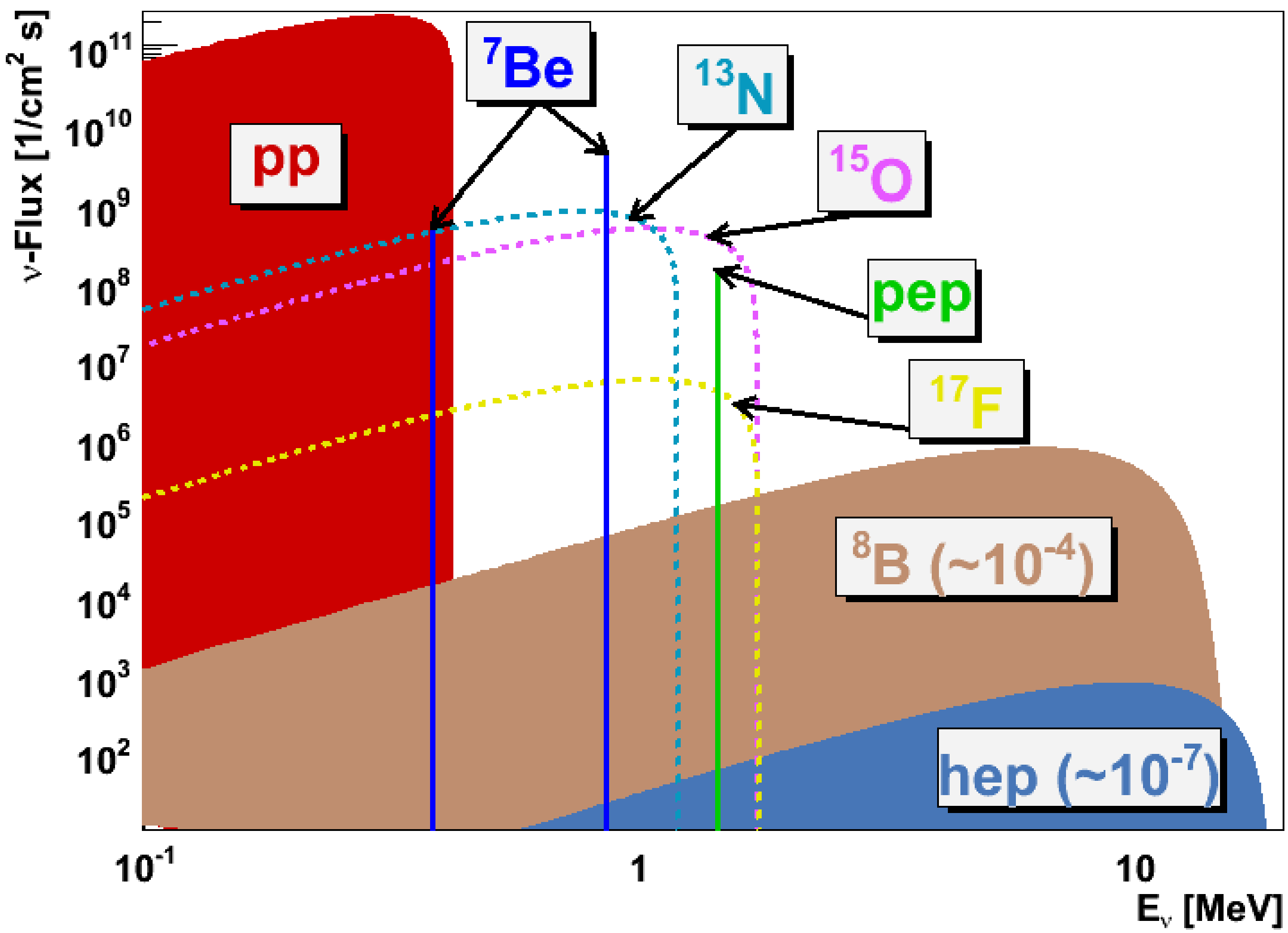
Who The LENS Collaboration

H. Back, I. Barabanov, J. Benziger, L. Bezrukov, J. Blackmon, A. Champagne, Z. Chang, A. Galindo-Urribari, A. Garnov, C. Grieb, V. Gurentsov, V. Kornoukhov, R. Hahn, J. Link, M. Pitt, *R. S. Raghavan*, S. D. Rountree, R. Tayloe, R. B. Vogelaar, E. Yanovich, M. Yeh, and A. Young

Institution	*Responsibility*
Va Tech	PI, Hardware & Infrastructure
Brookhaven	Scintillator
UNC & NCSU	Front-End Electronics
LSU	DAQ & Monte-Carlo
Indiana	Engineering & Shielding

Solar Neutrino Spectrum

- Solar neutrino spectral measurements limited to ^{7}Be and ^{8}B at E > 2.8 MeV
- Next step is precise spectroscopic measurements of the low energy neutrino fluxes from the sun – pp, pep, and CNO neutrinos
- Such measurements will continue to address important questions in solar physics and neutrino physics using this unique source – highest matter density, longest baseline, pure ν_e flavor at source, with the lowest neutrino energies.



Proposed Experiments to Measure pp Solar Neutrinos

ν - e elastic scattering (CC + NC)

- CLEAN (liquid neon)
- XMASS (liquid xenon)
- e-Bubble (liquid neon and helium)

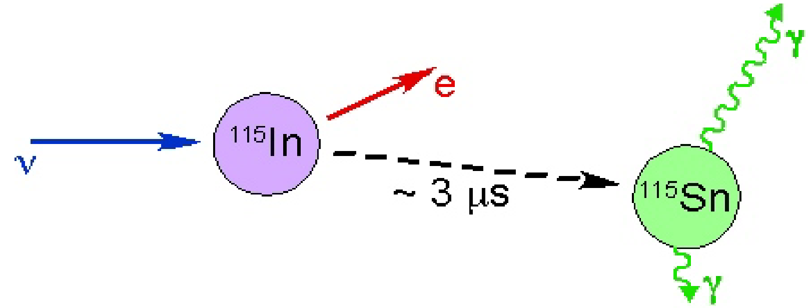
Tagged ν capture (CC only)

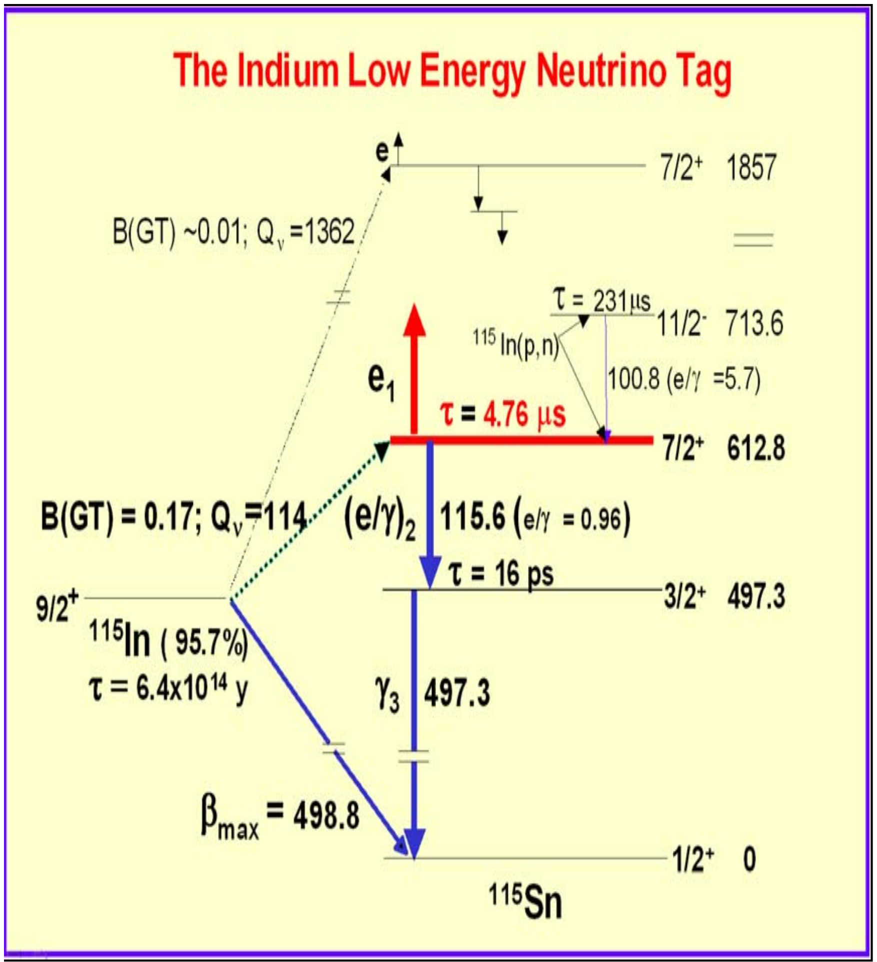
- LENS (tagged neutrino capture on ^{115}In)

The LENS Experiment

Technique: Tagged charged current neutrino capture on ^{115}In loaded (~8%) in liquid scintillator
(R.S. Raghavan, Phys. Rev. Lett. **37**, 259 (1976).

$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau = 4.76\,\mu s)} + {}^{115}Sn$$



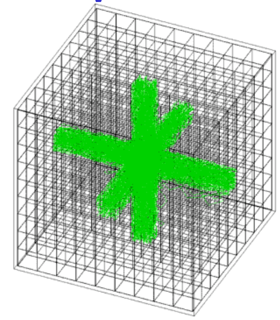


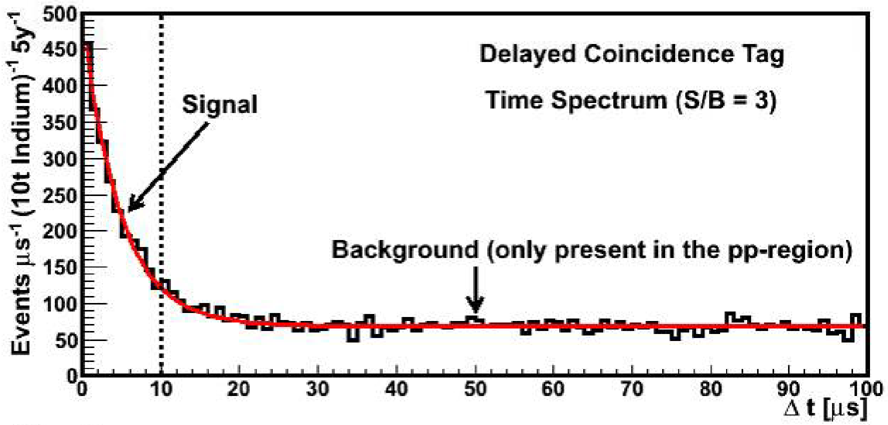
- ^{115}In abundance ~ 96%
- Low threshold = 114 keV (access to 95.5% of pp ν)
- Directly measures neutrino energy $E_\nu = E_e + Q$ (114 keV)
- Principle challenge: background from ^{115}In beta decay ($\tau_{1/2}$ = 6.4 x 10^{14} years) ($E_{endpoint}$ ~ 499 keV) (but this only affects p-p neutrinos, not ^{7}Be, pep, CNO neutrinos)

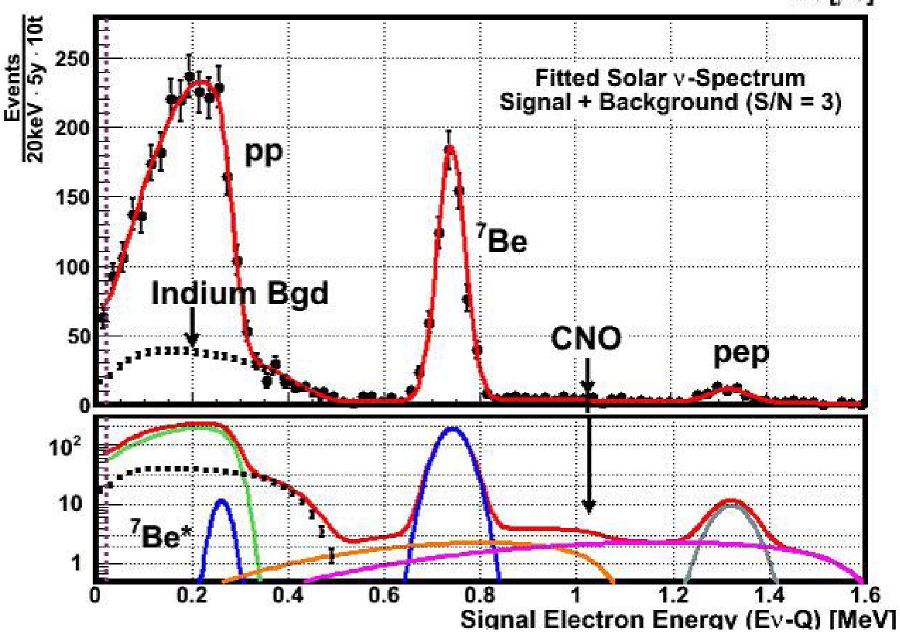
→10 tons In → 8 x 10^{13} decays/year (2.5 MHz) compare to 400 ν_{pp} events/year

Suppressing the Indium Beta Decay Background

The 3D scintillation lattice chamber concept allows for good spatial event localization with adequate energy resolution.







Primary background (random coincidences of In beta decays) can be suppressed through:

- Time/space coincidence tag
- Energy resolution (tag energy = 613 keV compared to < 500 keV In beta energy)
- cuts on shower topology

→ Background measured simultaneously at long delay times

Projected precisions in 5 years of running:

pp	3%
^{7}Be	4%
pep	9%
CNO	12%

LENS Science Objectives

Solar physics

1. Solar luminosity inferred from neutrino flux – compare to luminosity determined from photon
2. CNO flux - metallicity of the sun's core & stellar opacity; transport of CNO elements
3. Shape of the pp neutrino spectrum – sensitive to temperature and location of hydrogen fusion in the core

Neutrino physics

1. Precision test of MSW-LMA neutrino oscillations - energy dependence of P_{ee}
2. Place constraints on Standard Model extensions – non-standard interactions, mass-varying neutrinos, magnetic moments
3. Precision measurement of θ_{12}
4. Is there any evidence for sterile neutrinos at low energies?

LENS Science - Luminosity Comparison

Solar luminosity inferred from neutrino flux

$L_{\odot}^{\nu}$ assume proton-proton & CNO mechanisms

use *measured* ν–fluxes @ Earth

use self-consistent neutrino model

calculate ν–fluxes @ Sun

$L_{\odot}^{hf}$ → energy generated in Sun

energy generated in Sun *measured* by photon flux

$$L_{\odot}^{\nu} / L_{\odot}^{hf} = 1.4\left({}^{0.2}_{0.3}\right)_{1\sigma}\left({}^{0.7}_{0.6}\right)_{3\sigma}\ \text{(Bahcall)};$$

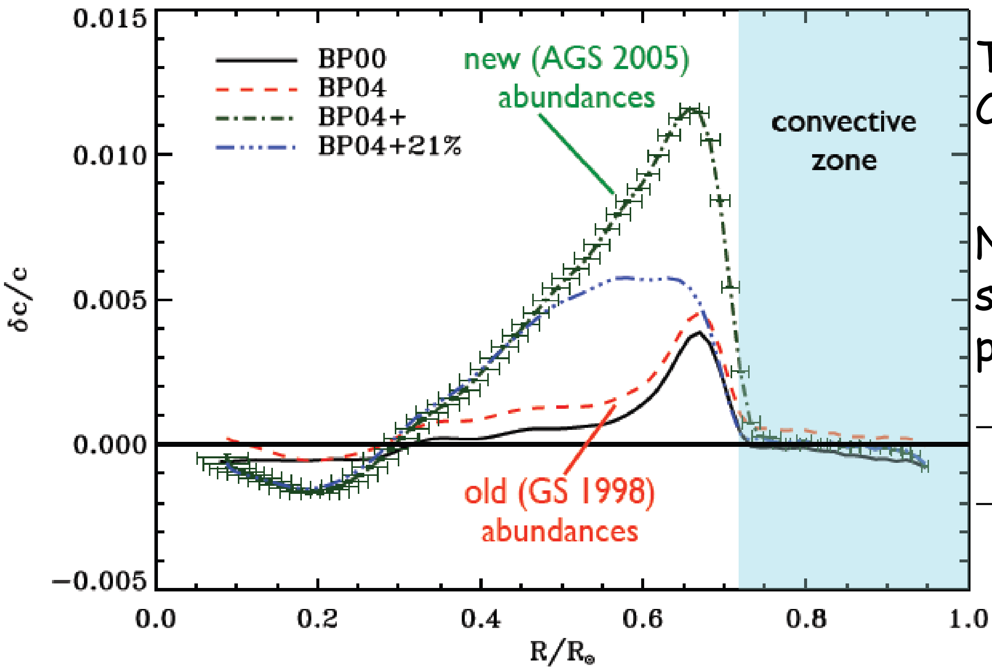
$$1.12(.21)\ \text{(Robertson)}$$

J.N.Bahcall and C.Pena-Garay, JHEP **0311**, 4 (2003) [arXiv:hep-ph/0305159].
R.G.H.Robertson, Prog. Part. Nucl. Phys. **57**, 90 (2006) [arXiv:nucl-ex/0602005].

More precise comparison of the current rate of energy production from fusion in the sun's core to the photospheric luminosity is desired to answer:

- Is the rate of energy production in the sun constant?
- Time variability of radiative zone?
- Is energy lost to magnetic fields?
- Is there another source of energy in the sun?

LENS Science – CNO Flux



The New Solar Neutrino Problem!—
C, N, O in the Sun?

New photospheric solar abundance analyses show 30-50% lower metalicities than previously

→Destroys agreement with helioseismology

→Reduces predicted CNO neutrino fluxes

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1\ ^{+0.19}_{-0.17})$	$3.25(1\ ^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

Measurements of CNO flux can shed light on this problem

Haxton/Serenelli: Cross- check of surface and core abundances would test key assumption of SSM – homogeneous zero-age Sun

W. Haxton, A. Serenelli, ApJ **687**, 678 (2008)

LENS Science Objectives

Solar physics

1. Solar luminosity inferred from neutrino flux – compare to luminosity determined from photon
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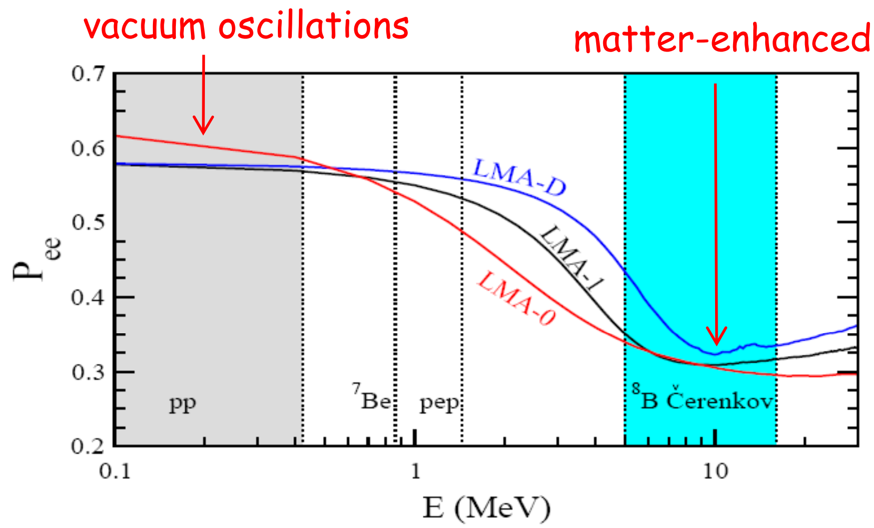


Non-standard interactions

A.Friedland, C.Lunardini and C.Pena-Garay, Phys. Lett. B 594, 347 (2004) [arXiv:hep-ph/0402266].
O.G.Miranda, M.A.Tortola and J.W.F.Valle, arXiv:hep-ph/0406280.

Critical LENS Technologies

The most critical technologies for making LENS perform to the needed specifications are:

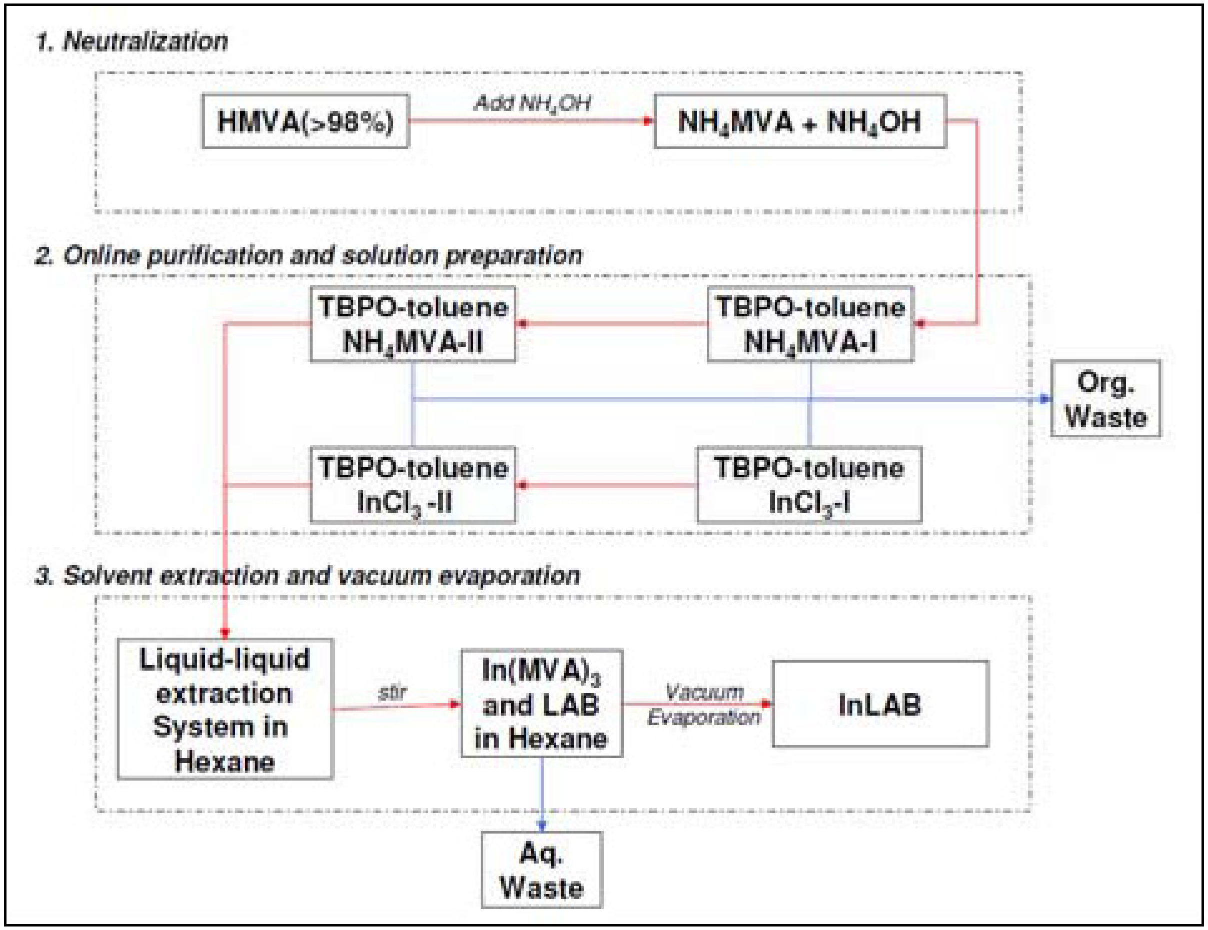
1. Metal-loaded liquid scintillator technology
   $\rightarrow$ allows an adequate amount of indium to be loaded in a stable liquid scintillator with long attenuation length

2. Three dimensional scintillation lattice structure
   $\rightarrow$ provides the necessary segmentation to achieve the spatial part of the background suppression

Scintillator Goals for LENS

- > 8% by weight of ^{115}In
- > 8 meter attenuation length
- > 35% light yield of unloaded pseudocumene (13000 photons/MeV)
- Stable properties over long times
- Low health and environmental hazard, low cost

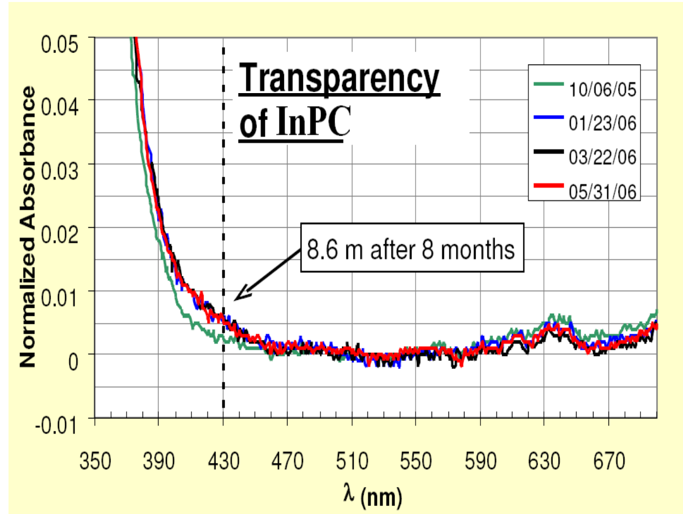
The synthesis procedure was developed at Bell Labs and improved over the past several years at VT.



Indium Loaded Liquid Scintillator Performance

The bulk of the initial work was done with pseudocumene (PC) as the scintillator but we have recently switched to linear alkylbenzene (LAB)

Metal loaded LS status	InPC	InLAB
1. Indium concentration	8%	8%
2. Scintillation signal efficiency	~8000 hν/MeV	~6000 hν/MeV
3. Transparency at 430 nm: L(1/e) (working value):	10m	8m
4. Light yield (Y%pc) (working value):	55%	36%
5. Chemical and Optical Stability:	Stable > 1 yr	L(1/e) degrades to ~2m after 30d. Oxidation of free HMVA?
6. InLS Chemistry	Robust	Robust



UV/Vis absorbance of zVt45 (pH 6.88) with time

Why InLAB when PC is good?

1. Availability in large quantity / Lower cost
2. Safer – Low toxicity
3. Higher flash point 140C vs 25C – better suited for underground applications
4. Better compatibility with plastics
5. Good optical properties

LENS Scintillation Lattice - Concept

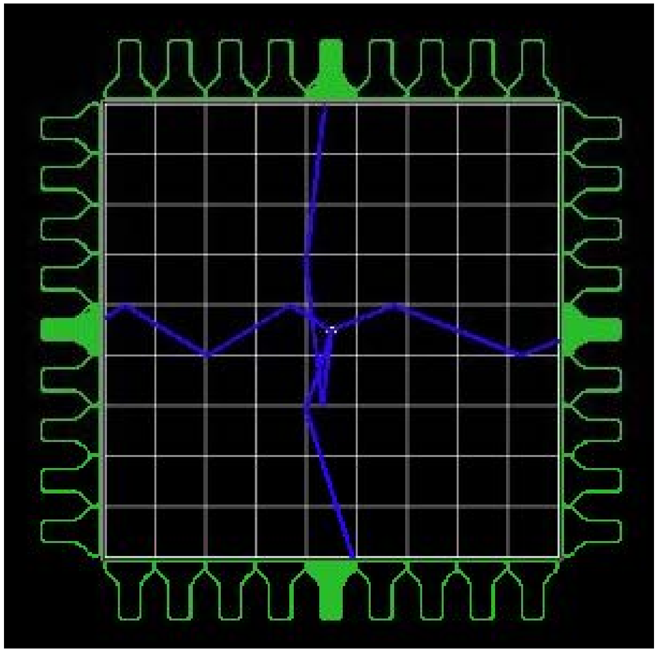
→ Optically segment (in 3D) a volume of scintillator
→ Use total internal reflection to channel the isotropically emitted scintillation light down axes of segmentation

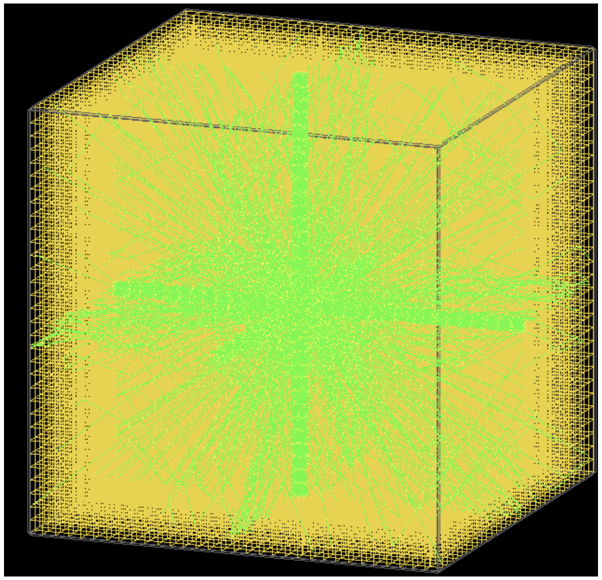
Ideal for cubic lattice: $\theta_{critical} = 45°$ → n = 1.07 → complete channeling (for n=1.52 scintillator)

$\theta_{critical} < 45°$, n < 1.07 → some light trapped in vertex cell
$\theta_{critical} > 45°$, n > 1.07 → some unchanneled light

Indices of some common materials:

Teflon FEP	n ~ 1.34
Water	n ~ 1.33
Perfluorhexane	n ~ 1.27
Air	n ~ 1.0





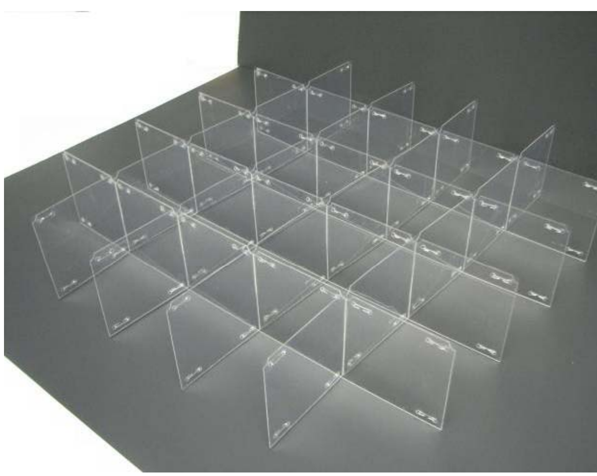
LENS Scintillation Lattice – Implementation

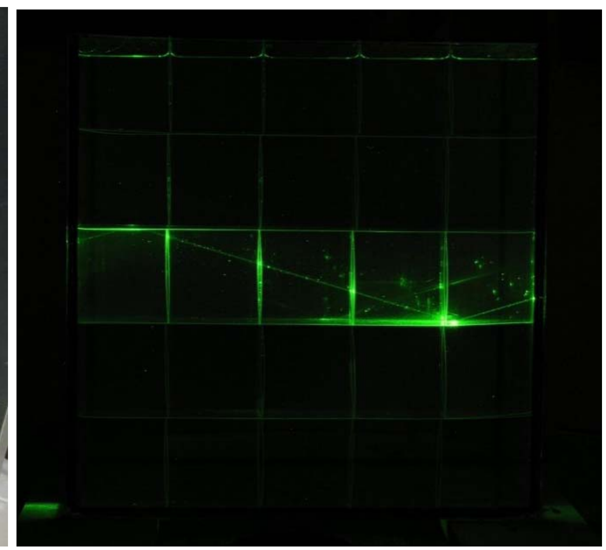
Solution: Teflon FPE n = 1.34 $\theta_{critical} = 62°$
about 50% of light channeled, good timing properties

Thin Teflon films (50 μm) tacked onto thin (0.4 mm) cast acrylic sheets (forming a teflon-acrylic or 'TA' layer)

Construction:

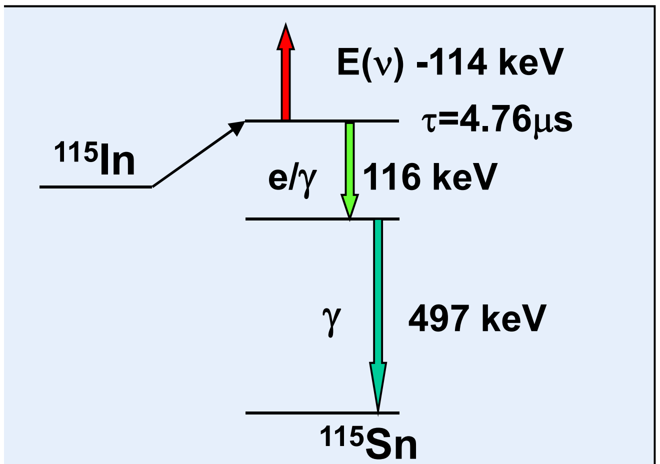
- Laser cut TA films into combs
- Interlock eight of them to form a 5x5 array of cubic cells (8.25 cm on a side)
- Stack five of these separated by flat TA films
- Forms basic unit of 5x5x5 cells
- Central LENS detector core would consist of 12x12x12 of these basic units

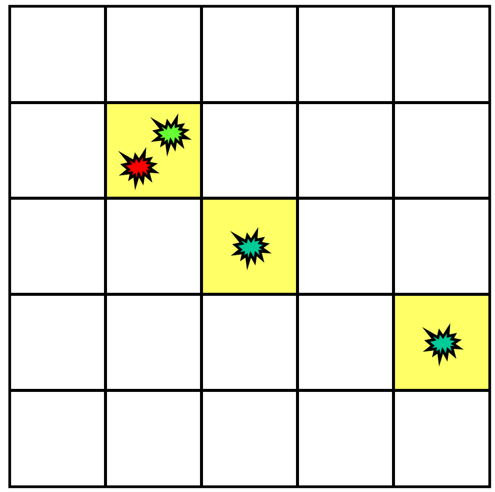




Indium β⁻-Background Topology – Space / Time coincidence

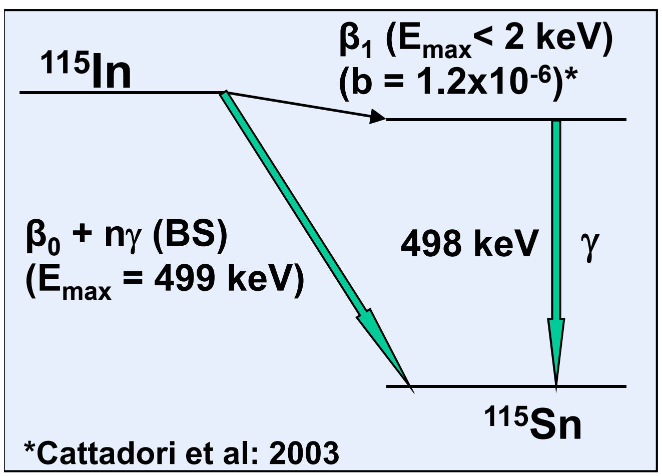
Signal



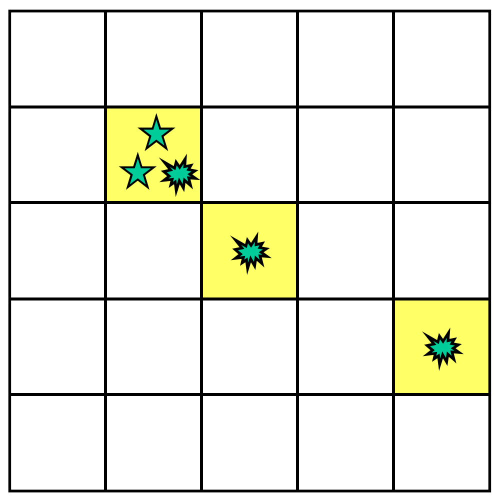


Signal Signature:

Prompt e^- (✸)
followed by
low energy (e^-/γ) (✸)
and
Compton-scattered γ (✸)



Background



Background:

Random time and space coincidence between two β-decays (★);
Extended shower (✸) can be created by:

a) 498 keV γ from decay to excited state;
b) Bremsstrahlungs γ-rays created by β;
c) Random coincidence (~10 ns) of more β-decays;

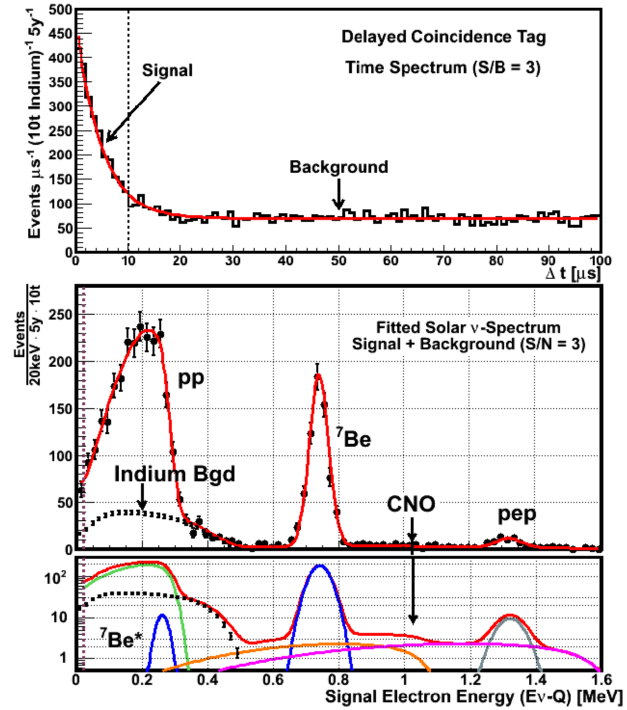
Or any combination of a), b) and c).

Indium β^--Background Discrimination

Background rejection steps:

A. Time/space coincidence in the same cell required for trigger;
B. Tag requires at least three ‘hits’;
C. Narrow energy cut;
D. A tag topology: multi-β vs. Compton shower;

Classification of events according to hit multiplicity;
➡ Cut parameters optimized for each event class improved efficiency;



Results of GEANT4 Monte Carlo simulation (cell size = 7.5cm, S/N=3) S/N=3; Bgd suppression 6x10^11)	**Signal (pp) y^{-1} $(t\ In)^{-1}$**	**Bgd (In) y^{-1} $(t\ In)^{-1}$**
RAW rate	**62.5**	**79×10^{11}**
A. Tag in Space/Time delayed coincidence with prompt event in vertex	**50**	**2.76×10^{5}**
B. + ≥3 Hits in tag shower	**46**	**2.96×10^{4}**
C. +Tag Energy = 613 keV	**44**	**306**
D. +Tag topology	**40**	**13 ± 0.6**

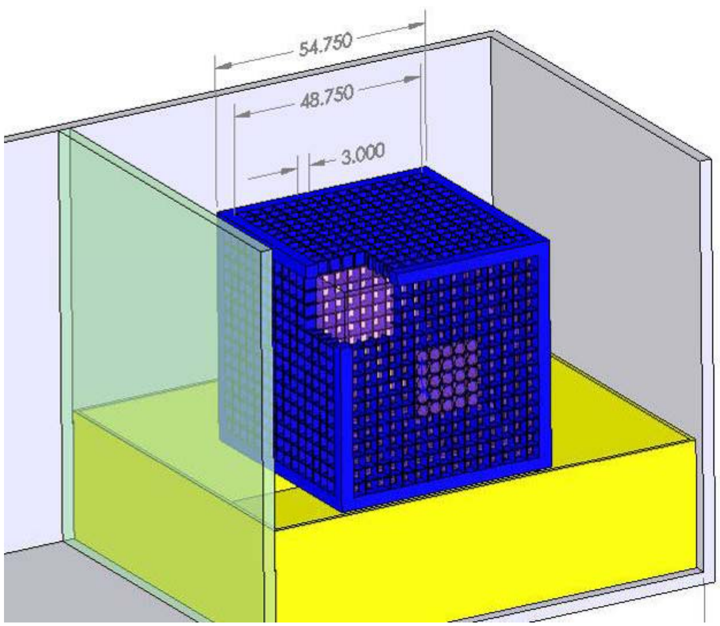
Reduction by ~$3 \cdot 10^{7}$ through time/space coincidence

Mini-LENS – A Testbed for LENS Technologies

To test the LENS technologies, we are constructing a ~ 1 m^3 prototype instrument (about 1% of volume of full LENS detector)

~ 5 kg Indium in center active region → 2.5 kHz In beta decay rate

- Topology of events in mini-LENS is identical to full LENS – allows the discriminating power of the geometry to be fully tested
- Measurements will be carefully bench-marked to Monte Carlo to establish the performance of the full instrument
- Will demonstrate all key aspects and establish scale-up route to full LENS
- Will be sited at the Kimballton Underground Research Facility – 1700 mwe depth

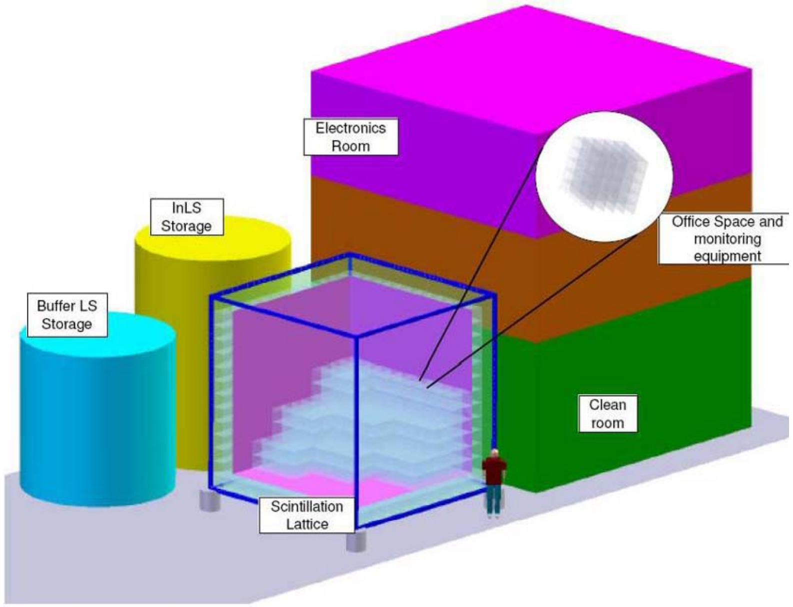


Full Scale LENS Experiment

Parameters of Full Scale LENS Experiment

- 125 tons of Indium loaded liquid scintillator (8% loading → 10 tons of Indium)
- 1728 of the 5x5x5 cell units in active region + 336 5x5x5 cells with unloaded scintillator as active veto
- ~ 21600 3 inch photomultiplier tubes
- Dimensions of scintillation lattice container ~ 5.8 m x 5.8 m x 5.8 m
- Anticipate ~ 400 pp neutrino events per year

The full scale LENS experiment is being designed to be housed in DUSEL – Deep Underground Science and Engineering Laboratory



Summary

Recent progress

- Indium loaded liquid scintillator technology
- Scintillation lattice chamber technology
- GEANT4 simulation of Indium beta decay background

makes a full scale LENS detector (10 ton indium, 125 ton InLS) appear well suited to make a precision measurement of the low energy (< 2 MeV) solar neutrino fluxes to:

- make precision comparison of neutrino and photon luminosity of the sun
- measure the CNO neutrino fluxes accurately
- generally probe a variety of interesting astrophysics and neutrino physics questions

Next steps:

- Build mini-LENS prototype detector to confirm and benchmark the simulations
- Pursue engineering design of the full-scale LENS detector and its ancillaries

Backups

Calibration of ^{115}In Neutrino Capture Cross Section

Needed for absolute neutrino flux measurements – in principle could be done with MCi manmade neutrino source but alternate way is to use the Borexino measurements:

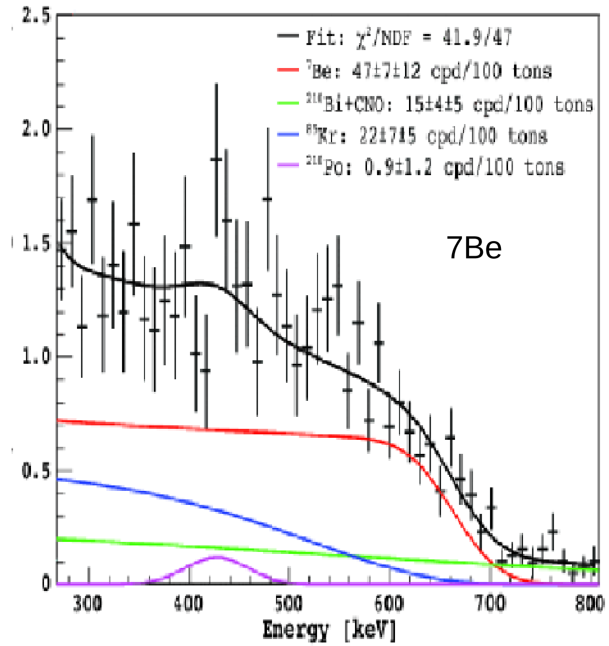
LENS and Borexino measure the same ^{7}Be ν flux with two different reactions:

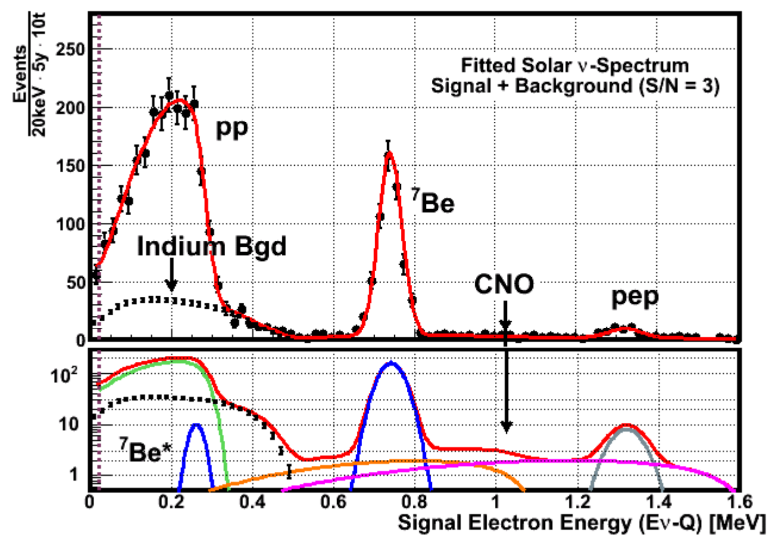
Borexino signal (R_B): $\nu_e + \nu_X$ (CC + NC)
LENS signal (R_L): ν_e only (CC)

$$R_B = \phi[p_{ee}\sigma_e + (1-p_{ee})\,\sigma_{\mu,\tau}]$$

$$R_L = \phi p_{ee}\sigma_c$$

$$\rightarrow \sigma_c = (R_L/R_B)\,[[p_{ee}\sigma_e + (1-p_{ee})\,\sigma_{\mu,\tau}]/\,p_{ee}]$$





Indium Loaded Liquid Scintillator – Work in Progress

- Begin testing of batches of In-loaded LAB using recently completed synthesis system flushed with inert gas (VT)

- Scaling up to a mini-LENS size production phases – 20 L batch production for a total volume of 125 L (BNL)

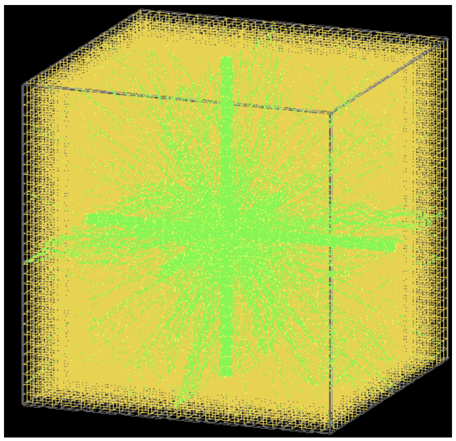
- Accelerated aging tests of InLS

- Accelerated aging tests of materials in InLS

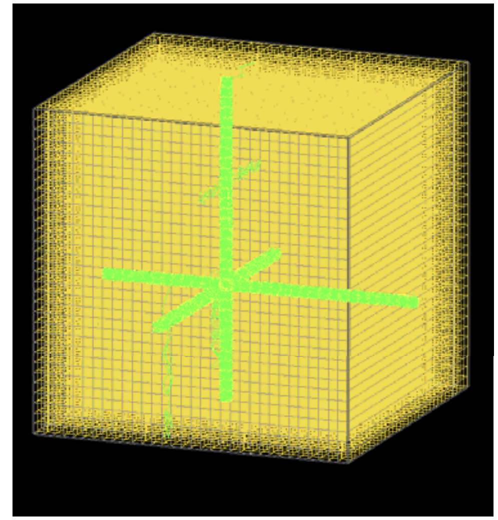
LENS Scintillation Lattice – Simulation Results

Simulation results from GEANT4

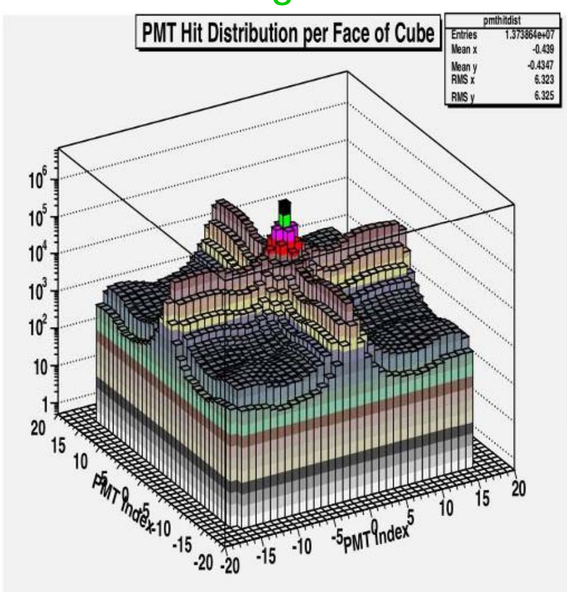
n=1.3



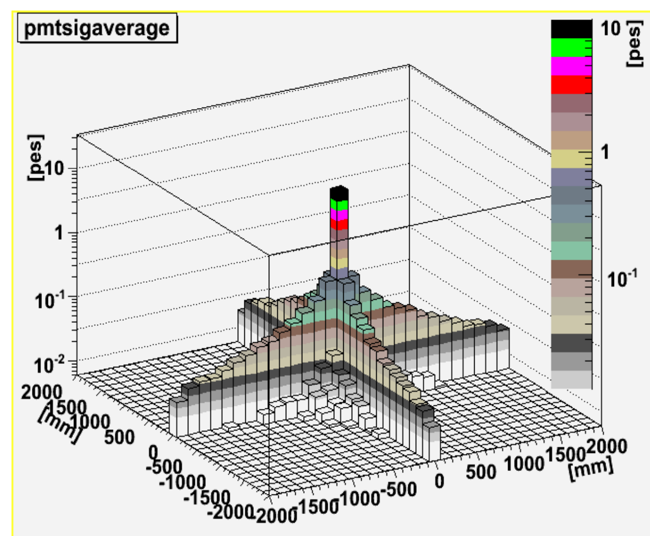
n=1.0



Solid Teflon segmentation



Double-layer (air-gap) lattice

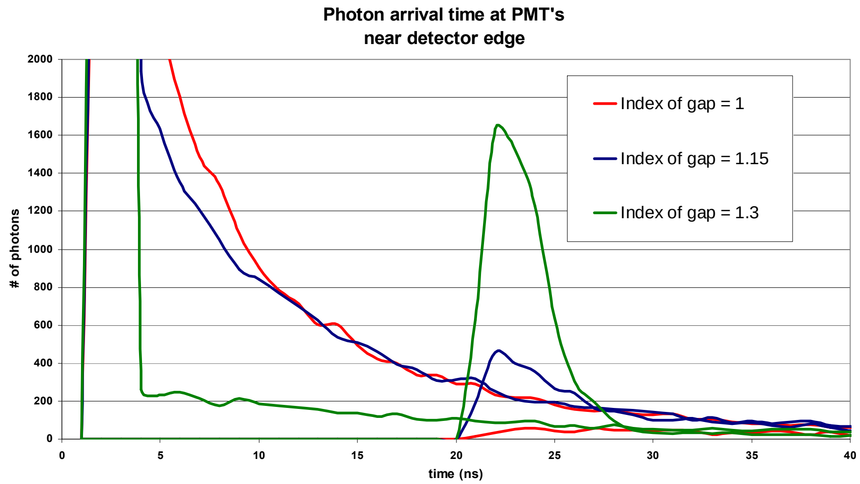


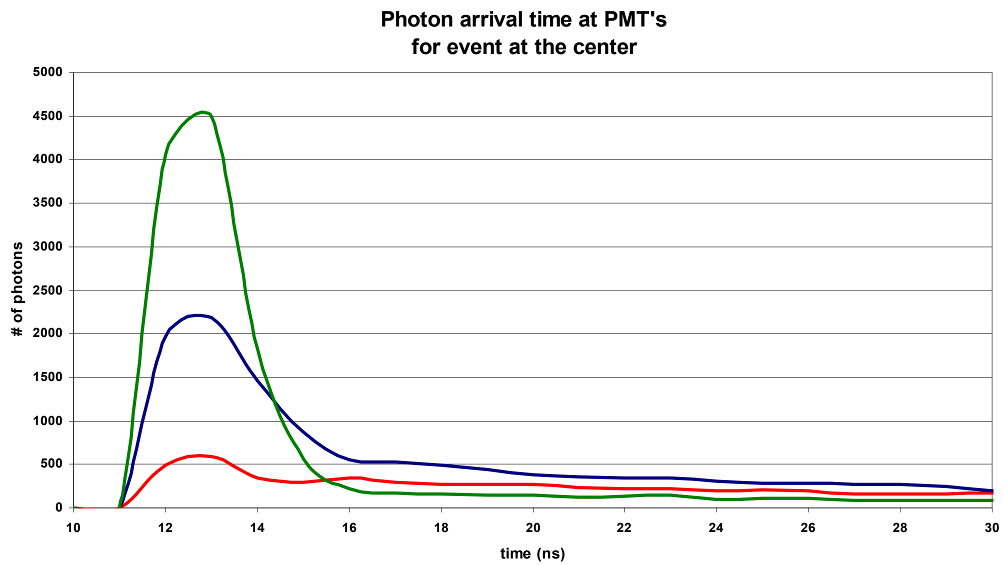
LENS Scintillation Lattice - Timing Simulations

Timing simulations show:

$\theta_{critical} < 45^o$, n < 1.07 → some light trapping
→ increase in average path-length and time dispersion

$\theta_{critical} > 45^o$, n > 1.07 → some unchanneled light
→ reduced average path length and better time dispersion





LENS Scintillation Lattice – Test in Ethylene Glycol

Demonstration of concept in lattice with acrylic – FEP teflon – acrylic cells filled with ethylene glycol (n ~ 1.43)

Mini-LENS Status

Mechanical design for MiniLENS

70 liter prototype (*μLENS*) is currently being constructed at VT

Construction of MiniLENS will begin after that

Electronics & DAQ

All major electronics (for 150 PMT's) on hand

Electronics being developed and tested now with few PMT's

μLENS to be shipped to LSU for DAQ development

Scintillator

Lab for intermediate scale production being developed

Infrastructure at KURF

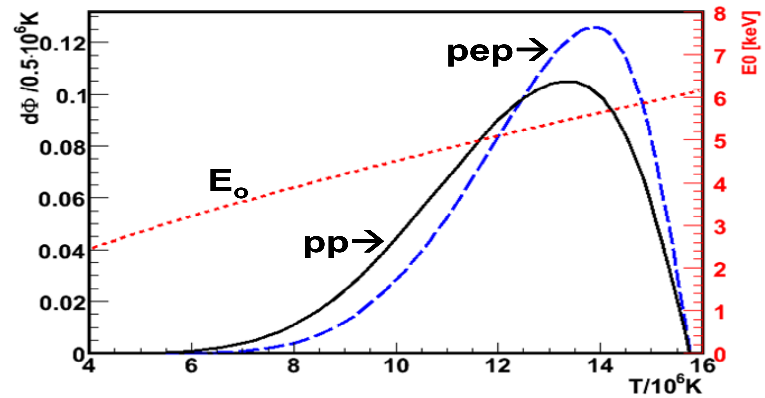
During Summer 2009 preparations are being made in KURF (Kimballton Underground Research Facility – 1400 mwe depth) to house mini-LENS (trailers, clean area for construction, etc.)

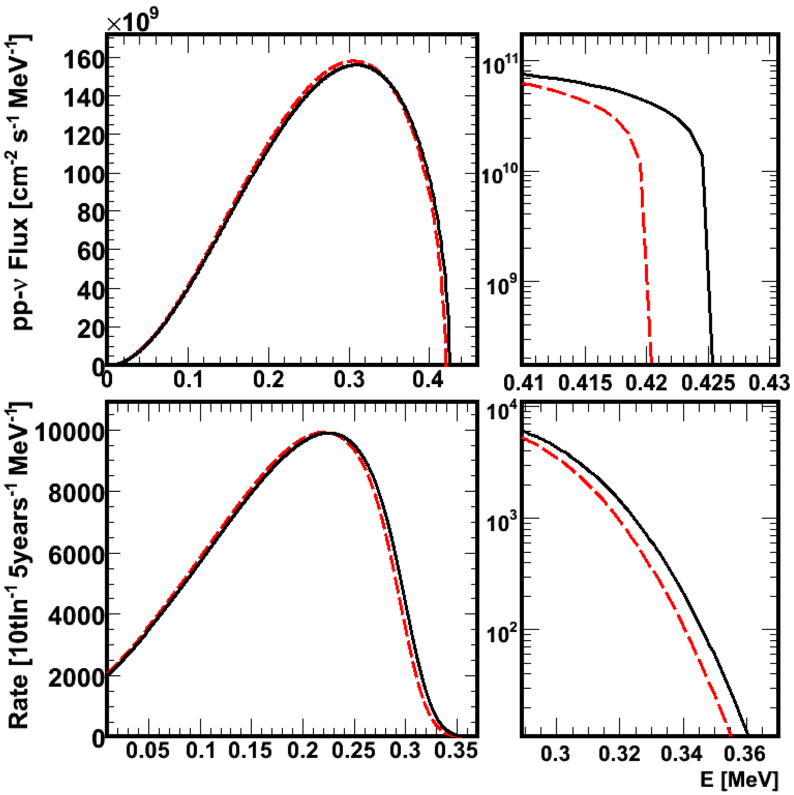
Goal is to have the 1 m^3 detector operating in KURF in ~ 2 years

LENS Science –
Probing the Temperature Profile of Energy Production in the Sun

Expected energy resolution in LENS would make it possible to observe the Gamow shift – the kinetic energy needed to initiate the pp fusion reaction

C. Grieb and R.S. Raghavan, Phys.Rev.Lett. 98:141102, 2007



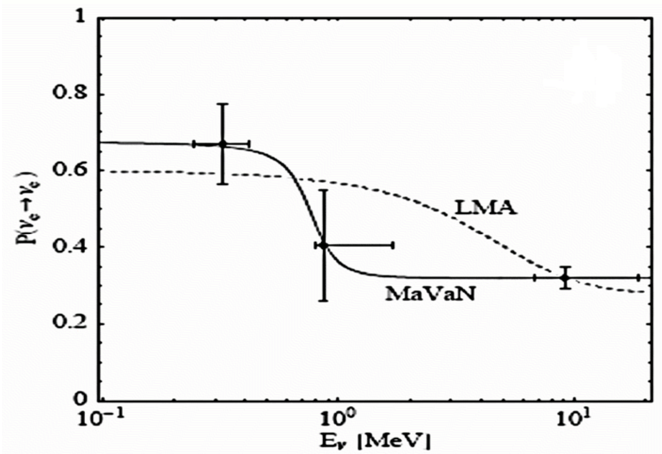


Top: pp-ν spectrum with/without Gamow shift

Bottom: Signal spectrum in LENS with/without Gamow shift
12t Indium - 6years
- δE/E=6% at 300keV

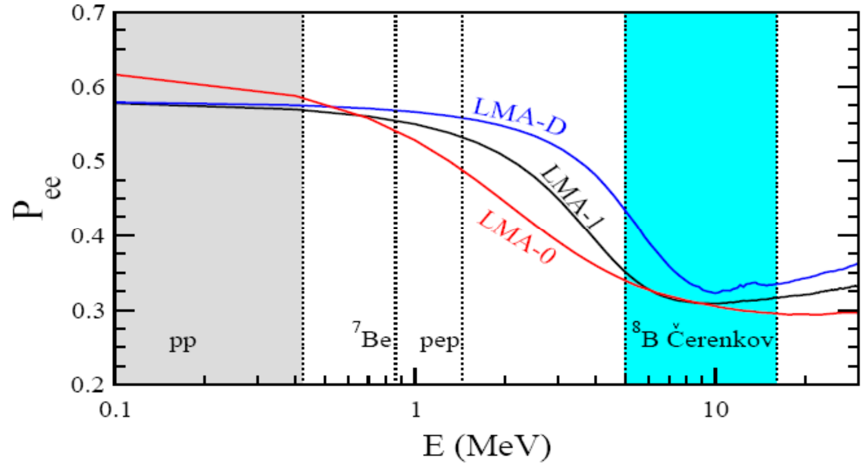
LENS Science - Neutrino Physics

Are there non-standard mechanisms involved?



Mass-varying neutrinos

Barger, Huber, Marfatia, arXiv:hep-ph/0502196v2 30 sep 2005



Non-standard interactions

A.Friedland, C.Lunardini and C.Pena-Garay, Phys. Lett. B 594, 347 (2004) [arXiv:hep-ph/0402266].
O.G.Miranda, M.A.Tortola and J.W.F.Valle, arXiv:hep-ph/0406280.

still need pp flux to confirm, since luminosity constraint is built into these predictions

Are there sterile neutrinos?

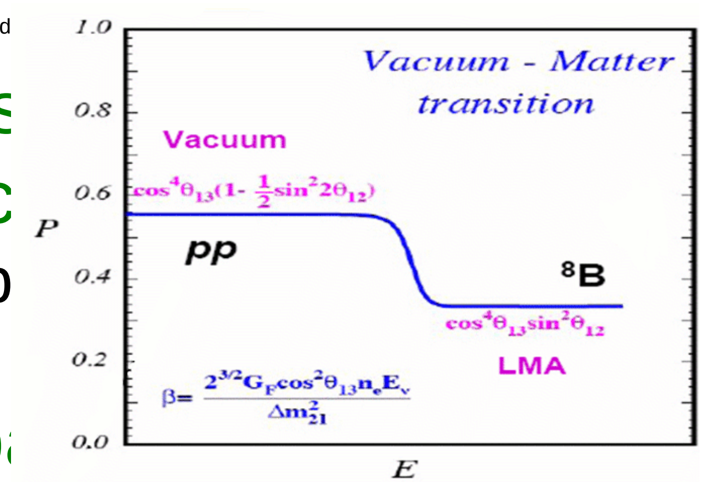
P. C. de Holanda and

Are there solar density fluctuations

Is CPT violated in the neutrino sec

do ν_e and $\bar{\nu}_e$ (from KamLAND) ob
the same results?

How much CNO? important for op

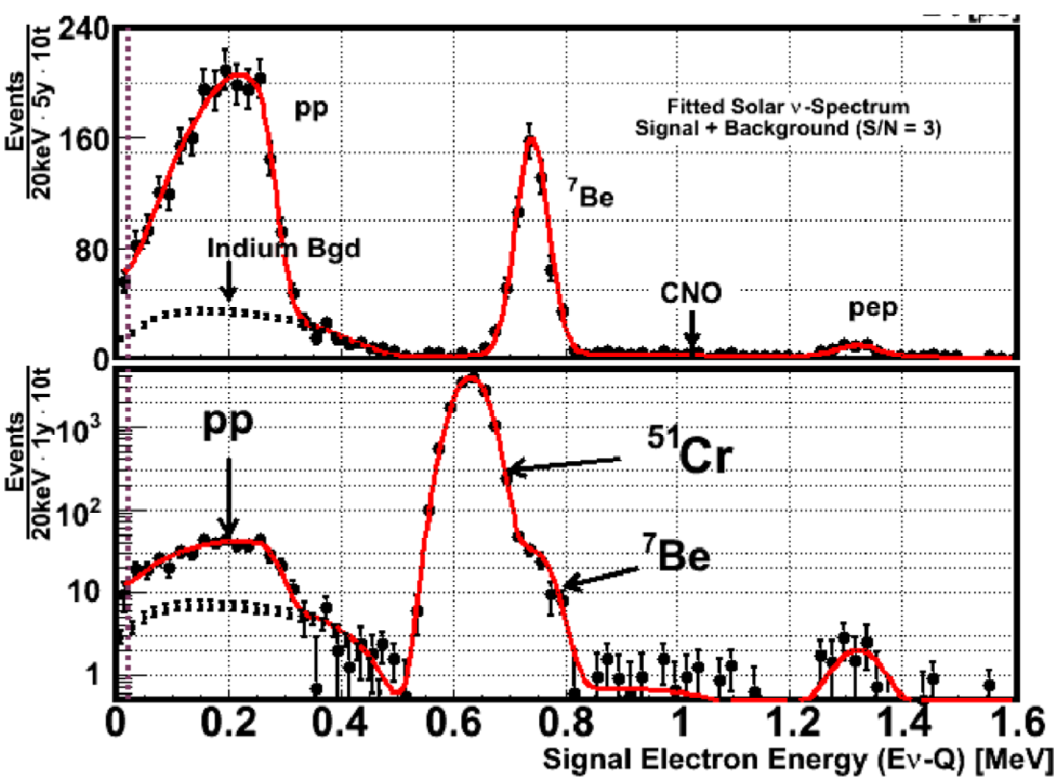


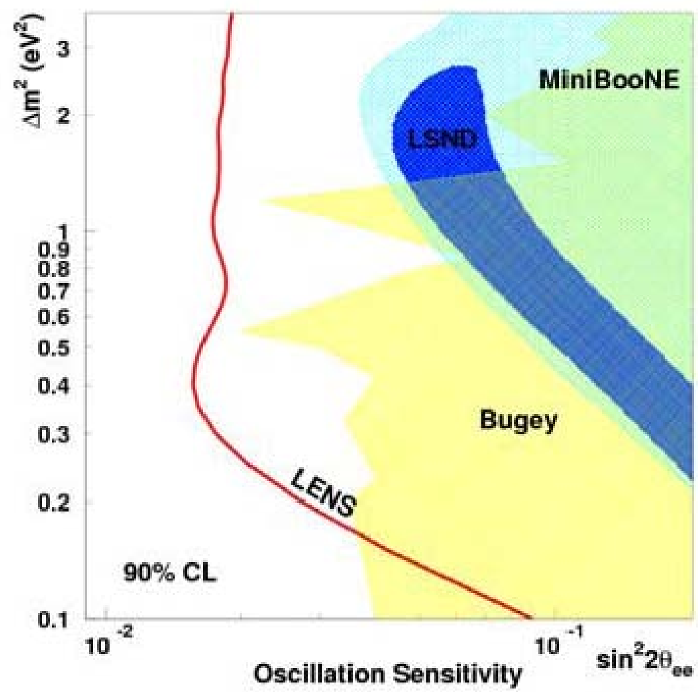
J. N. Bahcall and C. Pena-Garay, JHEP 0311, 004 (2003) [arXiv:hep-ph/0305159].

LENS Sterile

As a possible future applications of the low energy detection capabilities and segmentation of LENS, the possiblity of a sterile neutrino search in the $\Delta m^2 \sim 0.1 - 10\ eV^2$ range has been considered.

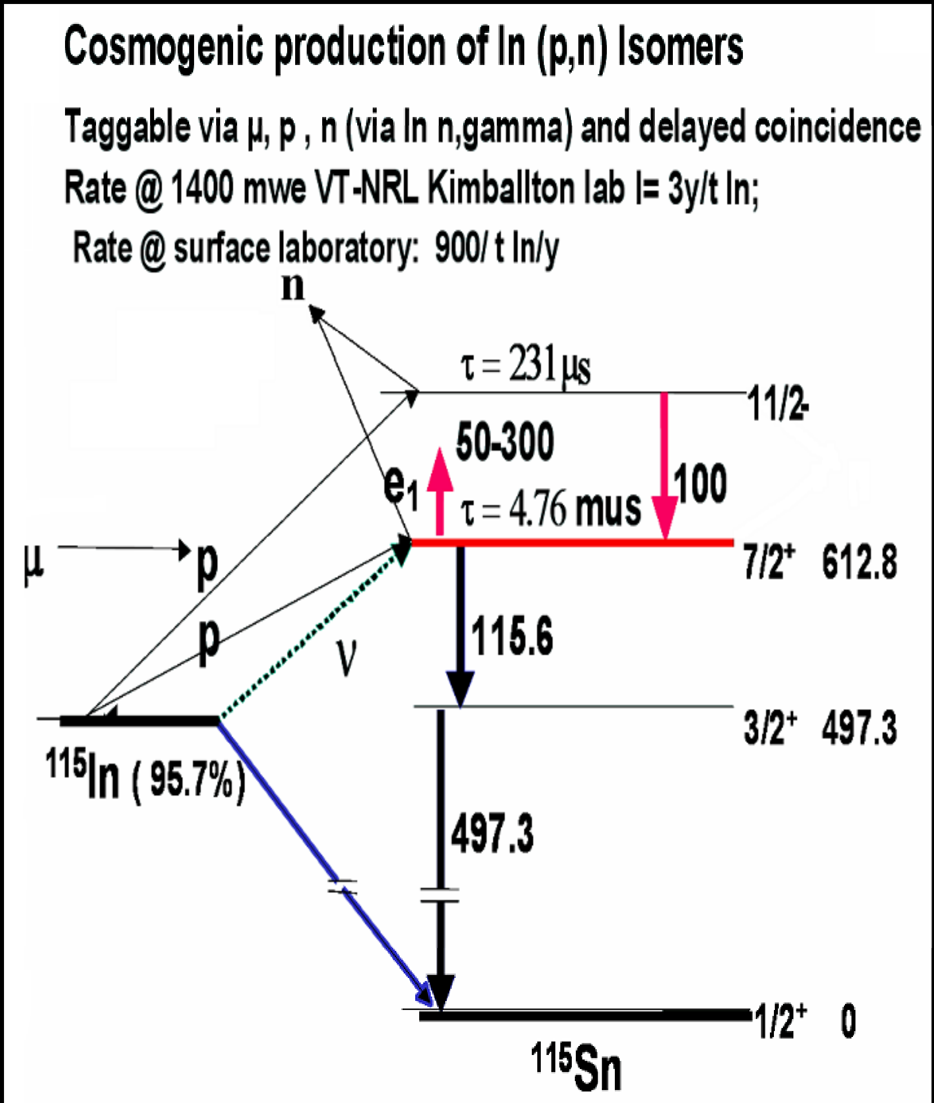
C. Grieb, J. Link, R.S. Raghavan, Phys. Rev. D **75**, 093006 (2007)

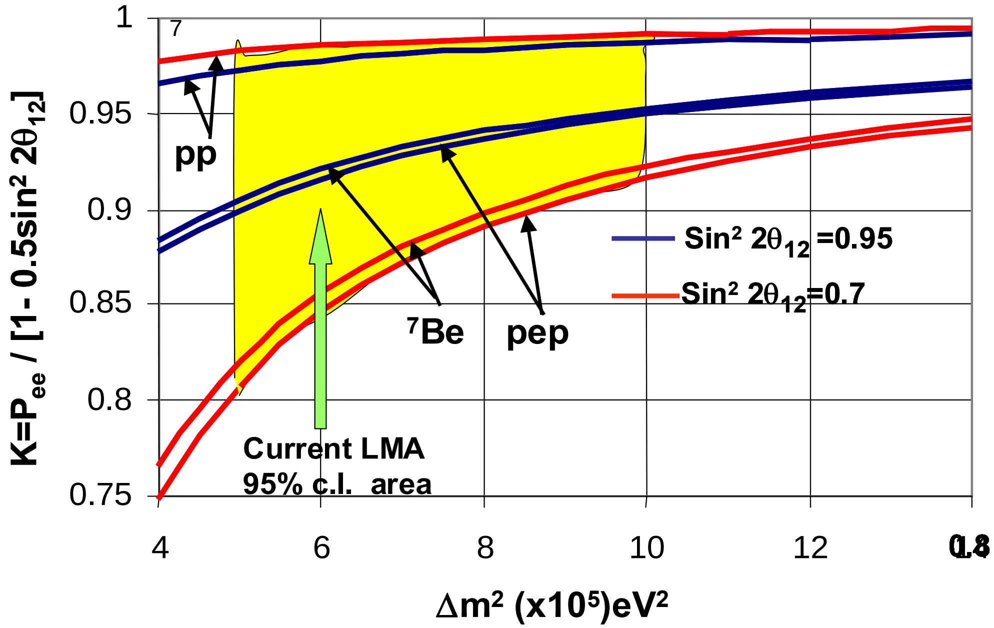




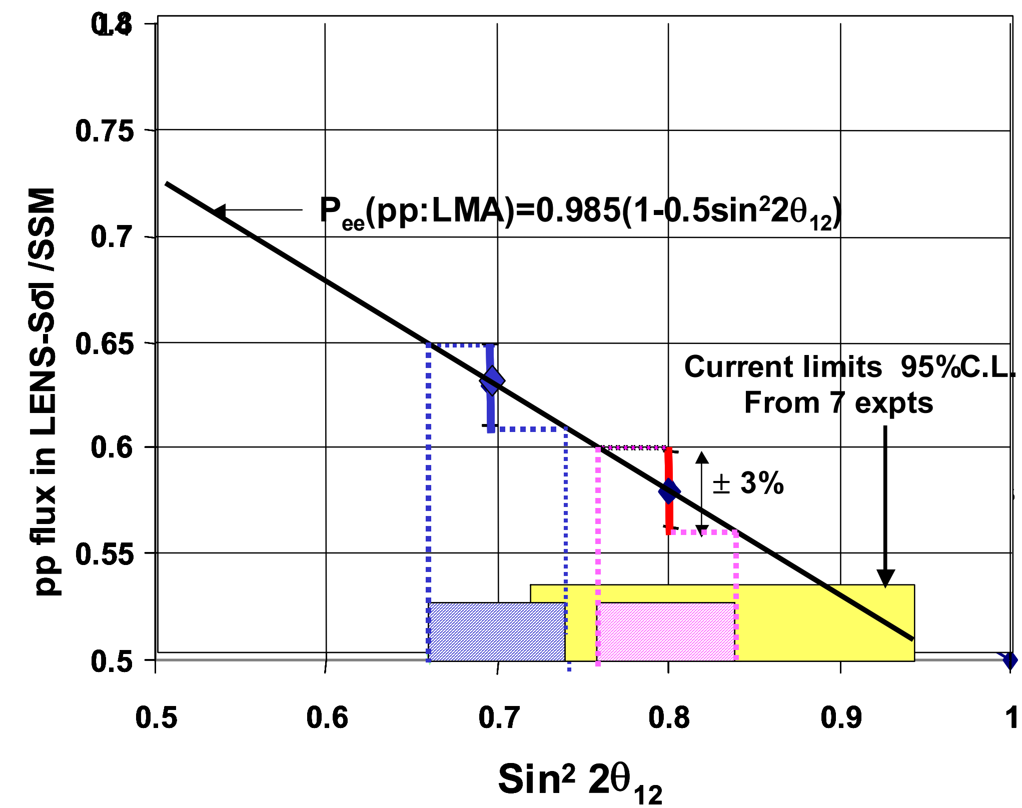
Cosmic pp Proxy Events

- 100keV gamma
- Exact excited state as neutrino capture
- Pretag with μ and p tracks





1
0.95
0.9
0.85
0.8
0.75
4
6
8
10
12
14
K=P_ee / [1- 0.5sin² 2θ12]
Δm² (x10⁵)eV²
pp
7Be
pep
Sin² 2θ12 =0.95
Sin² 2θ12=0.7
Current LMA
95% c.l. area

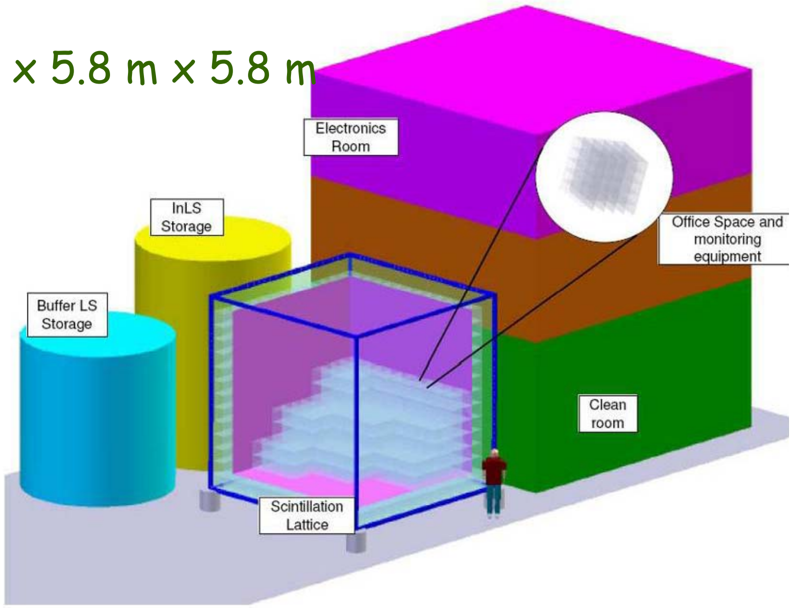


0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.5
0.6
0.7
0.8
0.9
1
pp flux in LENS-Sol /SSM
Sin² 2θ12
P_ee(pp:LMA)=0.985(1-0.5sin²2θ12)
Current limits 95%C.L.
From 7 expts
± 3%

Full Scale LENS Experiment

Parameters of Full Scale LENS Experiment

- 125 tons of Indium loaded liquid scintillator (8% loading → 10 tons of Indium)
- 1728 of the 5x5x5 cell units in active region + 336 5x5x5 cells with unloaded scintillator as active veto
- ~ 21600 3 inch photomultiplier tubes
- Dimensions of scintillation lattice container ~ 5.8 m x 5.8 m x 5.8 m
- Anticipate ~ 400 pp neutrino events per year



DUSEL S4 proposal submitted to NSF targeted towards engineering needed to deploy the full scale LENS instrument at DUSEL

- Structural engineering
  - Outer vessel
  - Infrastructure
- Scintillator
  - Scaling path for processing/purification
  - Storage and secondary containment underground

The timing of S4 with the simultaneous deployment of mini-LENS will allow the most cost-effective scale-up path to be defined.